

## Short Note

# Buildings as a Seismic Source: Analysis of a Release Test at Bagnoli, Italy

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**Abstract** Taking advantage of a large displacement-release experiment on a two-story reinforced concrete building located in Bagnoli (Naples, Italy), we performed free-field measurements using 3D seismometers, accelerometers, and a 100-m-long vertical array. The ground motion was noticeable: near the building, the acceleration exceeded 5%  $g$ . At each measurement point, it was possible to recognize two source terms, due to the tested building and to the reaction structure. The two sources generated different wave trains. High-frequency accelerations propagated as Rayleigh waves, whereas 1–2 Hz waves carrying most of the displacement propagated only as body waves. The experiment lends further support to the hypothesis that buildings are able to modify substantially the free-field ground motion in their proximity: the peak ground acceleration we observed is the 20% of the ground acceleration required to produce a displacement on the building equal to the one imposed during the release test. We recognize, however, the difficulty of a realistic modeling of wave propagation in the topmost layer of a densely urbanized area.

## Introduction

During an earthquake, the vibration of building transmitted back to the soil is able to modify the free-field ground motion. This idea was theoretically postulated by Wong and Trifunac (1975) and Wirgin and Bard (1996). During an earthquake it is difficult to measure and to separate the source and site effects from ground vibrations introduced by an oscillating building (Chavez-Garcia and Cardenas-Soto, 2002). Passive and active experiments have been carried out by Jennings (1970) during forced vibration of buildings, by Kanamori *et al.* (1991) studying the effects caused by the sonic boom of the Space Shuttle on high-rise buildings in Los Angeles, by Guéguen *et al.* (2000) and Guéguen and Bard (2005) on a five-story reinforced concrete (R/C) building model (1:3) located in the EuroSeis Test site at Volvi (GR), by Mucciarelli *et al.* (2003) on a base isolated building during a release test, and by Gallipoli *et al.* (2004) and Cornou *et al.* (2004) using ambient noise. The conclusions of all these experiments confirm the importance that buildings may have as seismic sources.

The availability of an existing R/C building to be demolished in the ex-Italsider steel works at Bagnoli-Naples, in the framework of ILVA-IDEM project (Mazzolani *et al.*, 2004), gave us the chance to carry out *in situ* large-displacement tests on a R/C frame.

## Experimental Setup

The test structure of the ILVA-IDEM Project is an old R/C building, built in the 1970s in the former industrial area of Bagnoli (Naples). The building originally had two stories, one span in the transverse direction and twelve spans in the longitudinal direction. The interstory height is about 3.0 m for both the first and second stories. The span length is 5.60 m in the transverse direction, and varies between 2.80 and 3.80 m in the longitudinal direction. Two structural engineering groups took advantage of the availability of this building to test retrofitting measures. The group of the University of Basilicata upgraded one bay of the structure in the transverse direction with four recentering braces based on the superelastic properties of NiTi shape memory alloys (full details on this experiment are given by Dolce *et al.*, 2004). To avoid any interaction with the structural elements, all internal and external infill masonry panels were demolished; then the structure was subdivided into six similar modules. For the experimental *in situ* tests, a steel-frame reaction structure was designed and built close to the building. It was able to exert both pull and push forces, up to about 300 kN. A steel vertical beam was tied to the R/C frame at both stories and connected to a hydraulic jack operated from the reaction

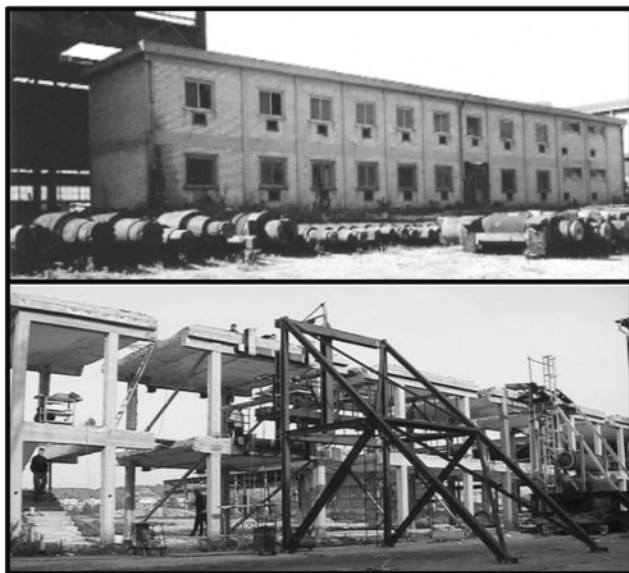


Figure 1. The office building at Bagnoli Steel Works before the experiment (top) and prepared for the release test (bottom). The bay studied by the University of Basilicata shows the dissipation braces and it is faced by the steel-frame reaction structure.

frame at an intermediate level. Figure 1 shows the building before and after the preparation phase. The mass of the building was about 35,000 kg and that of the reaction structure was 3100kg

Several cyclic and release tests were performed for engineering purposes. We measured the induced ground motion during a 7-cm displacement test. This displacement is representative of the maximum excitation that this kind of building might withstand during an earthquake. A displacement of 7 cm over a total height of about 6.5 m is close to 1% interstory displacement index (IDI). Exceeding this value may lead to heavy damage to nonstructural and structural elements of the building (Calvi, 1999; Mucciarelli *et al.*, 2001). A hydraulic jack displaced the building; the instantaneous release was obtained melting a steel fuse with a remote-controlled acetylene cutting system.

We monitored the building and the soil around it with several seismometers and accelerometers to study the behavior of the building during the release test, how the building transfers its energy to the soil and the ground-motion attenuation with distance from the building. The acquisition instruments were arranged according the scheme in Figure 2a: the vertical sensors were GeoSpace SD11 connected to a Geometrix 24-bit, 12-channel recorder; the accelerometer was a Kinemetrics ETNA, the seismometers were Mark LC4-3D except the closest in the longitudinal direction (a Lennartz 5s). The recording systems were Mars88/FD and Reftek-130. Before the release, we measured the fundamental frequency of building and soil, using the horizontal-to-vertical spectral ratio (HVSr) technique with a digital tromometer (Micromed Tromino). The measurement on the

building was carried out at the top floor to better estimate the fundamental frequency. The HVSr provides a good estimate of building fundamental frequency from single measurement points, as shown by Gallipoli *et al.* (2004) and Di Giulio *et al.* (2005). Moreover the building response during the test was estimated by horizontal accelerometers installed in different points of the building and at each floor, according to the scheme in Figure 2b.

## Results

The main frequency of the building estimated before the release test was slightly above 2 Hz; the result is shown in Figure 3. This estimation agrees with the one obtained for small oscillations by Dolce *et al.* (2004) by using accelerometers on the building. Figure 4 shows the short-time Fourier transform (STFT) (Gabor, 1946) of the acceleration recorded at the second level in the release direction; STFT produces a signal representation in both the frequency and the time domain to observe the variation in time of the spectral properties of the recorded accelerations. The method uses the Fourier transform for small sections of signal by using a windowing technique. To achieve well-fit results, a large number of points are necessary to pick the time-dependent frequency variations. At the same time, a short temporal window is needed to get a good description of the variations of the dynamic characteristics as a function of time, thus permitting to appreciate the variation of the fundamental frequency during the release test. The fundamental frequency of the frame is 2.4 Hz after the release test and during very small oscillations (purely elastic response), whereas for large displacements the fundamental frequency decreases to 1.2 Hz because of nonlinear behavior of the structure retrofitted with dissipation braces.

The steel frame acting as reaction structure had a design frequency in the range 20–30 Hz. This structure had no instruments placed on it.

The amplification function of the soil has two main frequencies, one at 0.4–0.5 Hz and the other at about 40 Hz. During the release test, there was no resonance between soil and building, and resonance between soil and the reaction structure is unlikely.

Figures 5 and 6 show examples of the recorded signals. In particular, Figure 5 reports longitudinal acceleration, velocity, and displacements recorded at the ground floor of the building and the longitudinal ground acceleration at 10 m from the structure. It is possible to see that acceleration is dominated by high frequencies (due to the reaction structure), whereas displacements are modulated by the 1–2 Hz predominant frequency of the building. Figure 6 shows the signals recorded with the vertical array, positioned obliquely with respect to the structure's principal axes. Note that the largest acceleration is at the second measurement point. No further data are available to explain this observation. A probable explanation could be due to the soil–structure interac-

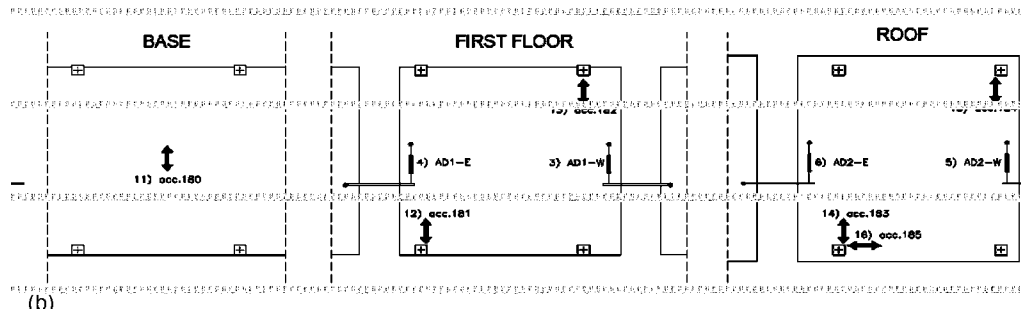
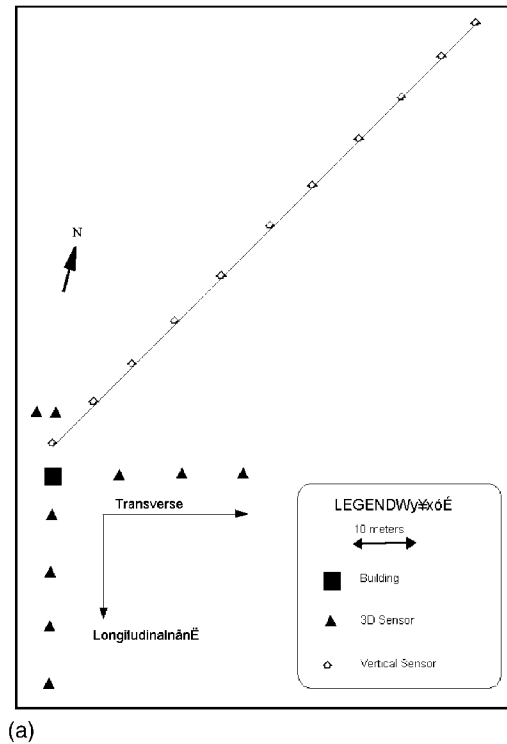


Figure 2. Arrangement of seismic instrumentation for measuring the ground motion induced by the instantaneous release of the building on the ground (a) and on the building (b). The black triangle 10 m north of the building is an accelerometer; all the others are seismometers.

tion, causing a reduction of soil rigidity and thus a smaller peak ground acceleration (PGA).

We corrected the data for a linear trending baseline and then filtered the time histories with a Butterworth fourth-order filter in the range 0.25–50 Hz. After derivation of the velocity time histories, we estimated the PGA at every measurement point (unfortunately, one sensor saturated and another one malfunctioned, so in the following text those data will be not included in graphs and discussion). Figures 7, 8, and 9 report the values for the vertical, north–south and east–west components, respectively. At 0 m for the longitudinal horizontal component, we report the value measured on the ground floor of the building. Note that the PGA exceeds 5% g in the vertical and north–south component (parallel to re-

lease), while the east–west component (perpendicular to release) yields lower values. We then performed an attenuation analysis on the strongest signals, that is, the north–south component along the longitudinal direction. We analyzed the attenuation of accelerations and displacements due to reaction structure and building, respectively. Figure 10 reports the PGA values together with two attenuation models. Position at 0 m reports the value measured at the buildings ground floor. Different coupling factors were considered. The reaction structure was bolted to a large R/C platform, thus maximizing the coupling with the ground. The foundations of the building were much less effective to transfer displacements to the ground, and we determined a 0.5 reduction factor (estimated empirically from best fit of the ob-

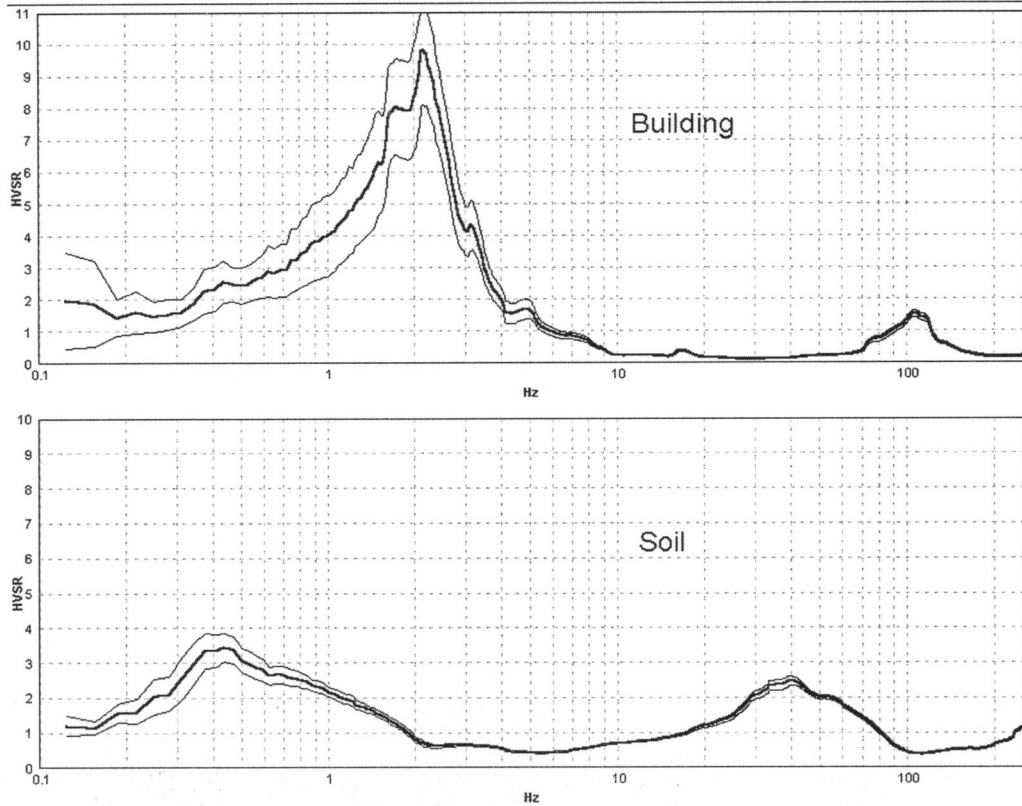


Figure 3. HVSR of building and soil, measured before the test. The thick line is the average; the thin line represents plus/minus one standard deviation.

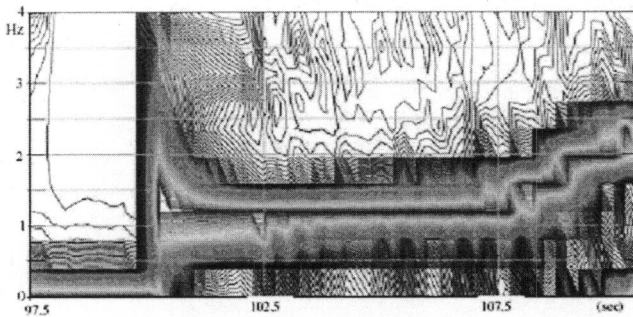


Figure 4. STFT (Gabor, 1946) of the braced frame-release test. The frequency is zero before the release, and then instantaneously drops from the elastic fundamental mode to a lower frequency, due to the anelastic behavior of the dissipating braces. After the large displacement phase the frequency for the small oscillation rises again above 2 Hz.

served data). We examined the possibility of having either body waves (attenuating as  $r^{-1}$ ) or surface waves (attenuating as  $r^{-1/2}$ ). In both cases, we also considered an inelastic attenuation with  $Q$  equal to 10, which is reasonable for the alluvial sediments the site of Bagnoli stands upon. It is possible to see that the best fit is with body-wave attenuation even if at longer distances ( $>20$  m) the acceleration values are also comparable with surface-wave attenuation. The

peak ground displacement (PGD) values are reported in Figure 11: the measured values are close to the body wave inelastic attenuation model. In this case, the elastic and inelastic attenuation models have comparable values because the wavelength involved in the displacements is about 50 m, so the inelastic contribution is not significant.

To further check the nature of the observed waves, we carried out a particle motion analysis on the measured signals. The two subsequent parts of the signal, characterized by two different frequency contents, have shown a different behavior: for the high-frequency waves at the beginning of the recording the reverse ellipticity due to the predominance of Rayleigh waves is clearly visible, and the polarization gives a neat, vertical major axis. The 1–2 Hz waves dominating the latter part of the signal are polarized in the transverse direction, as expected from a unidirectional source, with a  $45^\circ$  major axis possibly resulting from coexisting Rayleigh and shear waves.

## Discussion

The analysis on the recorded signals shows the importance of the reaction structure. High-frequency, high-acceleration waves at the beginning of the recordings are due to the steel reaction structure. In the latter part of the signals



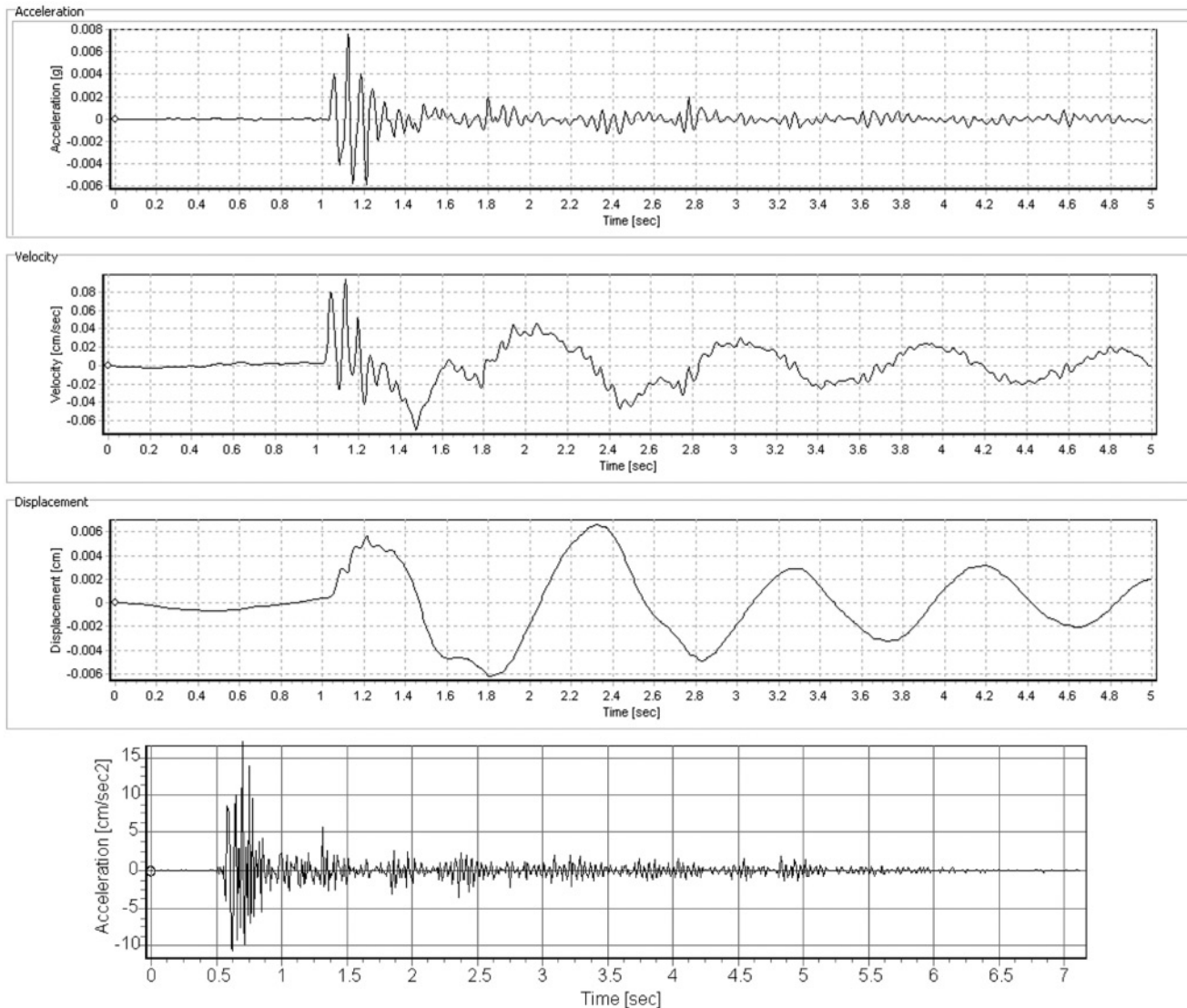


Figure 5. From the top, longitudinal acceleration, velocity and displacements recorded at the ground floor of the building and the longitudinal ground acceleration at 10 m from the structure. The timing is not absolute; pretrigger varies for the two instrumentations used.

low-frequency displacements excited by the building are predominant. The vibration from the reaction structure decays more rapidly with time because of the shorter period of this structure; the vibration from the building lasts longer because of its relatively longer period.

The main point to discuss is if our findings support the idea that building motion can significantly modify free-field ground motion. First, we check if the ground motion we observed is a significant percentage of the ground motion expected from an earthquake. The highest PGA we observed is 5%  $g$  with a 7-cm displacement of a structure whose frequency was in the range 1–2 Hz. If we consider the standard 5% damping-response spectra provided by the Italian Seismic Code, a 6-cm displacement at 1 Hz is obtained for the Zone 2–Soil A spectrum, whose PGA is 0.25 $g$  (see Fig. 12).

Thus the observed PGA is about 20% of the hypothetical unmodified free-field PGA.

This is already a nonnegligible modification of free-field ground motion, but we have to point out three reasons why what we observed could be a lower boundary value. First, the total mass of the building plus the reaction structure reaches only 38,100 kg, which is two times the mass of the Volvi model described by Guéguen *et al.* (2000) and Guéguen and Bard (2005), but still below the mass of a full-functional building, because of the lack of infills, services, and internal loads. Second, the coupling with the ground plays an important role in the efficiency of the structures as wave generators, as shown by the reaction frame bolted to a large R/C slab, with a better coupling with the ground with respect to the small, direct foundation of the test building.

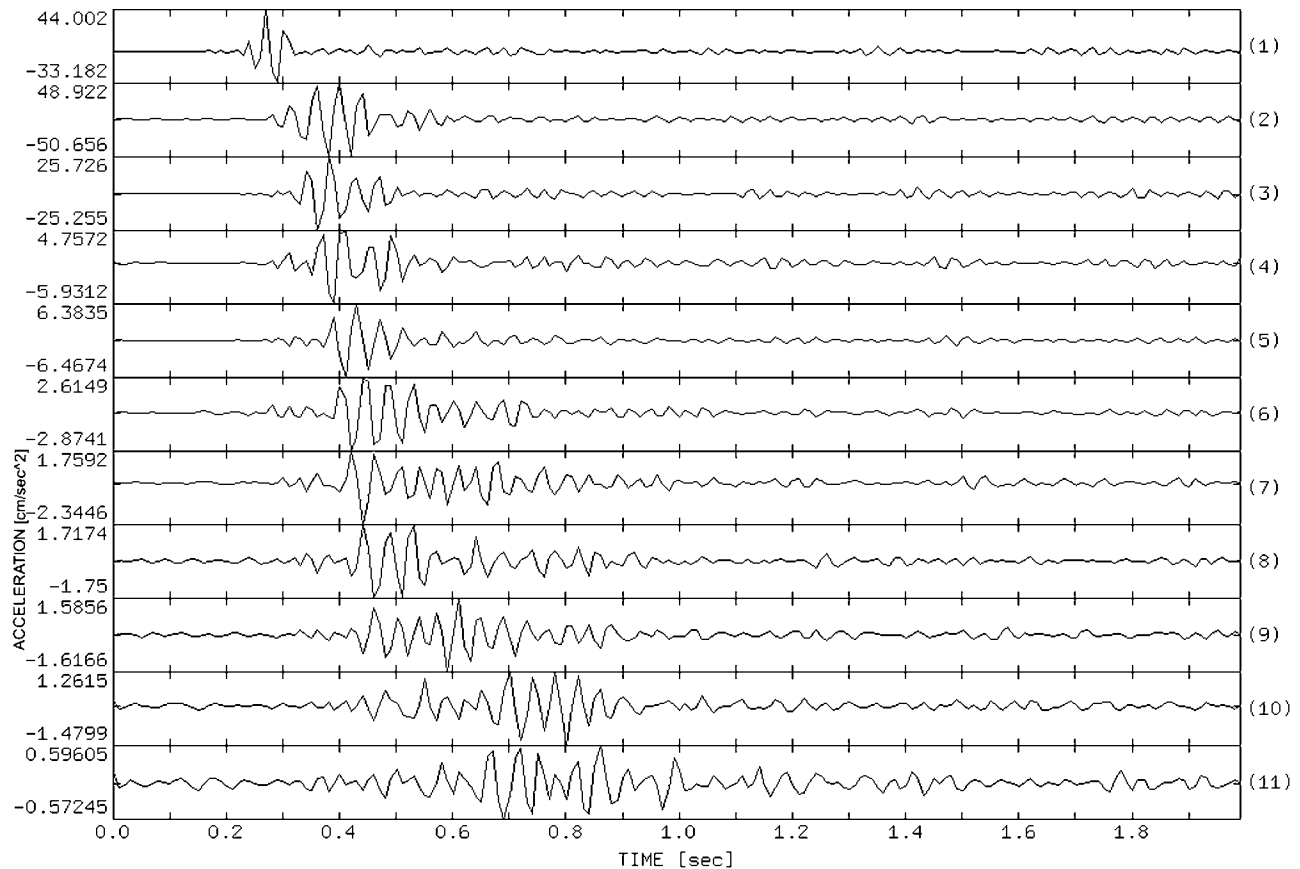


Figure 6. Acceleration recorded along the vertical-component oblique array (spacing, 10 m).

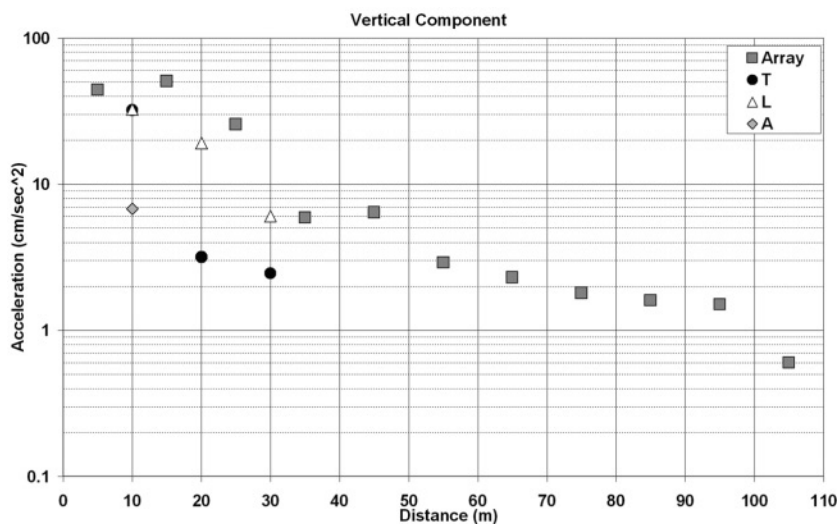


Figure 7. PGA values of the vertical component recorded by T and L array and by a free-field accelerometer 10 m north of the building. No vertical component was available at the base of the building

Taller buildings, besides having much larger masses, have deeper foundations, so a higher coupling factor is expected in an actual city–soil interaction. Third, there is a lack of soil–building resonance in the Bagnoli test. Bard *et al.* (1996) and Cornou *et al.* (2004) pointed out the importance of trapped waves in a resonant layer as a cause for far away propagation of structure frequencies. In our case, no reso-

nance is present between soil and building, and thus the observed values are a lower bound. Even with these limitations (reduced mass, poor coupling, and lack of soil–building resonance) a realistic displacement of the building (1% IDI) is able to produce a PGA exceeding 5% *g*, that is, 20% of the PGA needed to obtain such a displacement. This lends further support to the hypothesis that during an earthquake the

## Short Note

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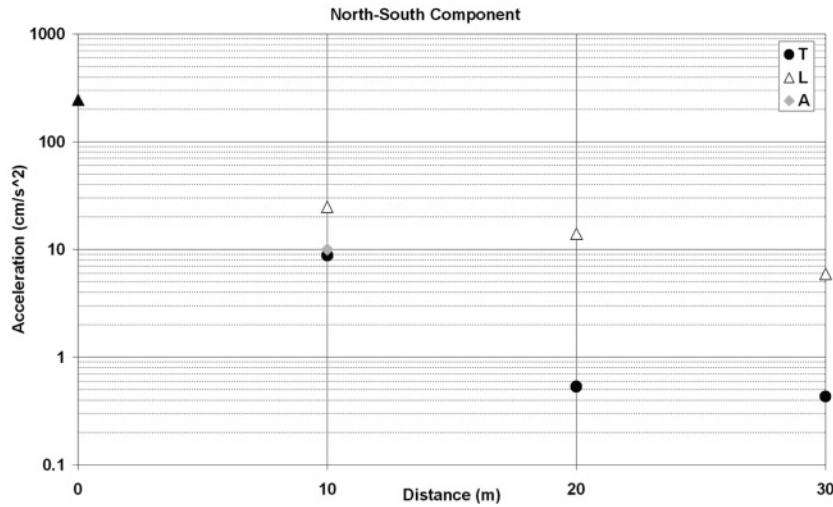


Figure 8. PGA values of the north-south component recorded by T and L array, by a free-field accelerometer 10 m north of the building, and by the accelerometer at the base of the building.

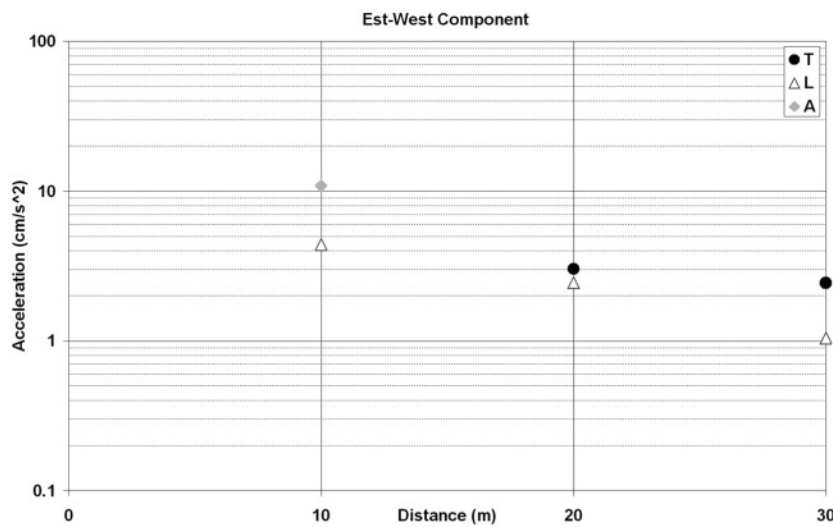


Figure 9. PGA values of the east-west component recorded by T and L array and by a free-field accelerometer 10 m north of the building.

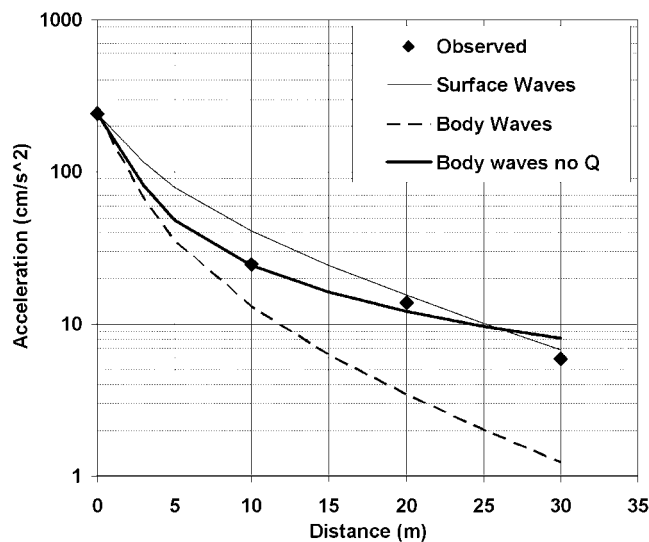


Figure 10. Attenuation model along the release direction of the PGA values of the north-south component, for comparison with theoretical decay.

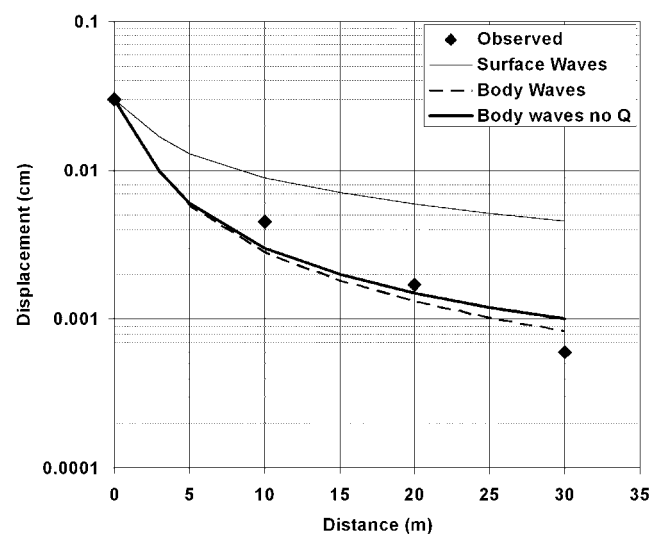


Figure 11. Attenuation model along the release direction of the PGD values of the north-south component for comparison with theoretical decay.

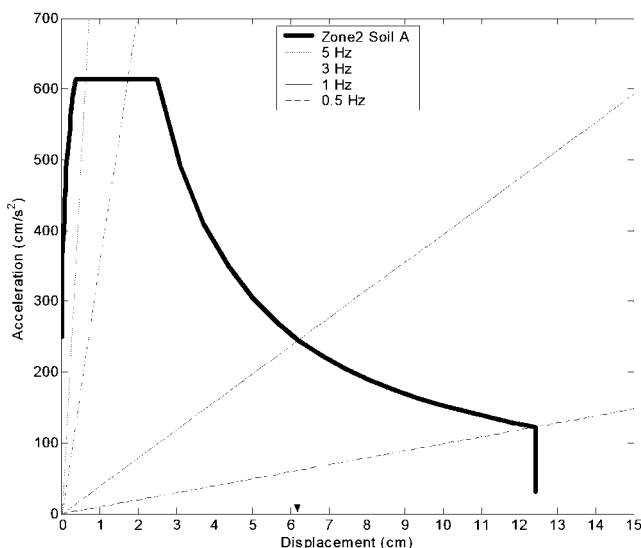


Figure 12. Acceleration-displacement response spectrum for the standard design input from Italian Building Code, Seismic Zone 2, Soil Class A. The arrow indicates the displacement expected for a structure vibrating at 1 Hz with 5% damping.

energy released back to the soil by vibrating buildings is able to modify the free-field ground motion.

The novelty of this experiment is that this was not a test-site model or a single building in a nonurbanized area. The tested building was in the middle of a densely industrialized area, where excavations, fills, foundations, and roads perturbed the topmost soil layers. This poses a further problem for detailed, realistic simulations of wave propagation near the surface of a densely urbanized area.

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